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The study of mid-infrared dual-band angle-insensitive and high-sensitivity absorber based on metamaterial structure

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Abstract: In this paper, we propose the design of an narrowband absorber based on a Square ring structure metamaterial nanostructure composed of a periodic array of Au Square ring and a gold (Au) film. The proposed structure can achieve a dual-band, nearly perfect absorption with a maximum absorbance of 99% and a full-width-athalf-maximum (FWHM) value that is less than 50 nm in the mid-infrared region. The polarization insensitivity is demonstrated by analyzing the absorption performance with normal incidences for both transverse electric (TE) and transverse magnetic (TM) polarized waves. In addition, we discuss the impact of change the incident angle and Polarization angle on the absorption performance in detail. The proposed narrow, dual-band metamaterial absorber shows promising prospects in applications such as infrared detection and imaging.

1. Introduction

Metamaterial devices have attracted substantial attention due to their marvelous electromagnetic performance in many applications such as antenna systems [1], [2], electromagnetic cloaking [3], imaging [4], ultra-sensitive sensing [5] and refractive index engineering [6]. The subwavelength structure of the metamaterials can be tailored flexibly by designing the artificial “meta-atoms”. This characteristic enables the metamaterials a designable permittivity and permeability. Meanwhile, the performance of the energy depletion in metamaterials can be utilized in a positive way to design metamaterial absorbers by introducing the power loss.

During the last decade, trends to achieve light absorption in metamaterials and plasmonic nanostructures have increased tremendously due to the huge interest in the development of solar energy harvesting. Generally, regarding the absorption bandwidth, absorbers can be categorized into two types, namely narrow band absorber and broadband absorber. The former one can easily find applications in linear or nonlinear sensors covering both visible and infrared regions [7]. On the contrary, in the applications such as photodetectors [8], thermal emitters [9], photovoltaics (PV) [10] and ultra-short pulse generation [11], broadband absorbers are always required. Up to date, plenty of metamaterial structures have been reported to demonstrate broadband perfect absorbers. For instance, using hole array [12], cylinder array [13], complementary crosses and cylinders [14] and multilayer structures [15]. However, these methods may suffer from the problems such as a relatively narrow absorption bandwidth (i.e. 300 nm - 400 nm) [16] complicated cell pattern or a requirement of noble metals[17].

In this paper, we design an narrow dual-band absorber based on a metamaterial nanostructure composed of a periodic array of gold square ring structure. The proposed structure can achieve a dual-band nearly perfect absorption at 4.65 um and 7.65 um from 4 um to 9 um, respectively. The absorption rate of the two absorption peaks is above 99%. Through the simulation study of the electric field power and magnetic field power distribution of the two resonance absorption peak, to analysis the absorption mechanism of the two absorption peaks. The extremely strong angle-insensitive properties of this metamaterial structure are demonstrated by changing the incident angle of the incident electromagnetic wave. Moreover, this nanostructure is straightly compatible with high throughput manufacture technology using soft nano-imprinting lithography, making the low-cost mass-production of the material highly feasible. It is expected that such absorber structure will hold great potential in harmful gas detection and photodetector applications.

2. Model and method

2.1. Model

The model structure of the wideband absorber is shown in the Fig 1, in which (a) is a 3D structure diagram, and (b) is a top view of the structure. The electromagnetic absorber is composed of gold square ring structure and the dielectric layer is SiO_2, The unit cell period is P = 3um, a is the side length of the outer square ring, b is the side length of the inner square ring and a=1.5um, b=0.9um. The width of the inner and outer rings is the same, both are 100nm. The numerical simulation is carried out using FDTD Solutions software. In terms of parameter setting, the periodic boundary conditions are set in both the x and y directions, and the perfect matching layer (PML) boundary conditions are set in the z direction. In addition, the plane electromagnetic wave with the electric field E parallel to the x direction is incident along the x-z direction, and the wavelength of the electromagnetic wave is taken to be 4-9 um.

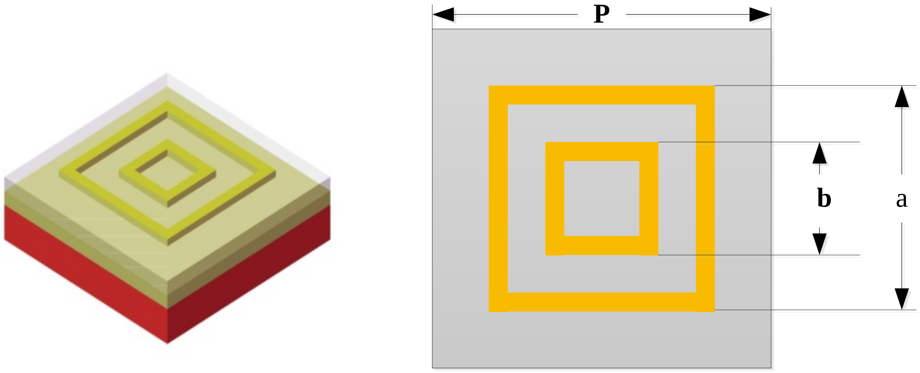


Fig 1. square ring structure Metamaterial absorber model based on MDM structure

In the case of normal incidence of TM polarized electromagnetic waves, the two absorption peaks shown in Fig 2. is obtained. There are two narrow resonance absorption peaks in the Fig 2., located at 4.65um and 7.65um, respectively. The absorption rate of the two resonance absorption peaks can reach more than 99%, and the half-peak width is less than 50nm. Due to the extremely narrow half-peak width, this square ring nanostructure metamaterial has extremely high sensitivity in the mid-infrared band. In order to study the two resonances mechanism of the two absorption peak, we simulated the electric field energy level distribution and the magnetic field energy level distribution of this metamaterial structure respectively.

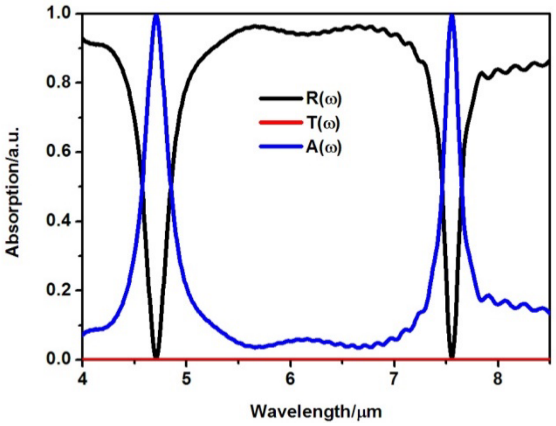


Fig 2. The metamaterials Narrowband Absorption peaks

2.2. Method

Electromagnetic fields generated by the interaction between incident electromagnetic waves and such non-magnetic surface plasmon resonance metamaterials, can be described in detail by the Maxwell equations [13,14].

$$\nabla \times \vec{H} = \varepsilon_0 \varepsilon_r \, \partial \vec{E} \big/ \partial t \tag{1}$$

$$\nabla \times \vec{E} = -\mu_0 \, \partial \vec{H} \big/ \partial t \tag{2}$$

In the Maxwell equations, $\vec{H}$ and $\vec{E}$ represents the magnetic field strength and electric field strength respectively, ε_r is representative of the dielectric permittivity of the dielectric material, ε_0 and μ_0 represents the vacuum permittivity and vacuum permeability respectively. In the numerical simulation the optical properties of Au and SiO_2 were measured using the parameters of Olmon and Palik in the experiment. The permittivity of the silica was chosen to be 3.9, the minimum structural element of the numerical simulation is shown in Fig 1.. The boundary condition in the Z direction of the model is the perfect match layer, in the X and Y directions, the smallest structural units are symmetrically arranged in positive and negative ditection, the boundary condition selects the periodic boundary condition.

In the numerical simulation process is used the FDTD(finite-difference time-domain method) to solve Maxwell equations, the electric field strength and the magnetic field intensity at the surface plasmon resonance of the excitation field is obtained. The absorption spectrum and the reflection spectrum of this absorber in the direction perpendicular to the incident electromagnetic wave can be obtained by the following equation.[11,12]

$$T_\lambda = \int S(x,y)\,dxdy \Big/ Q_{\lambda_i} \tag{3}$$

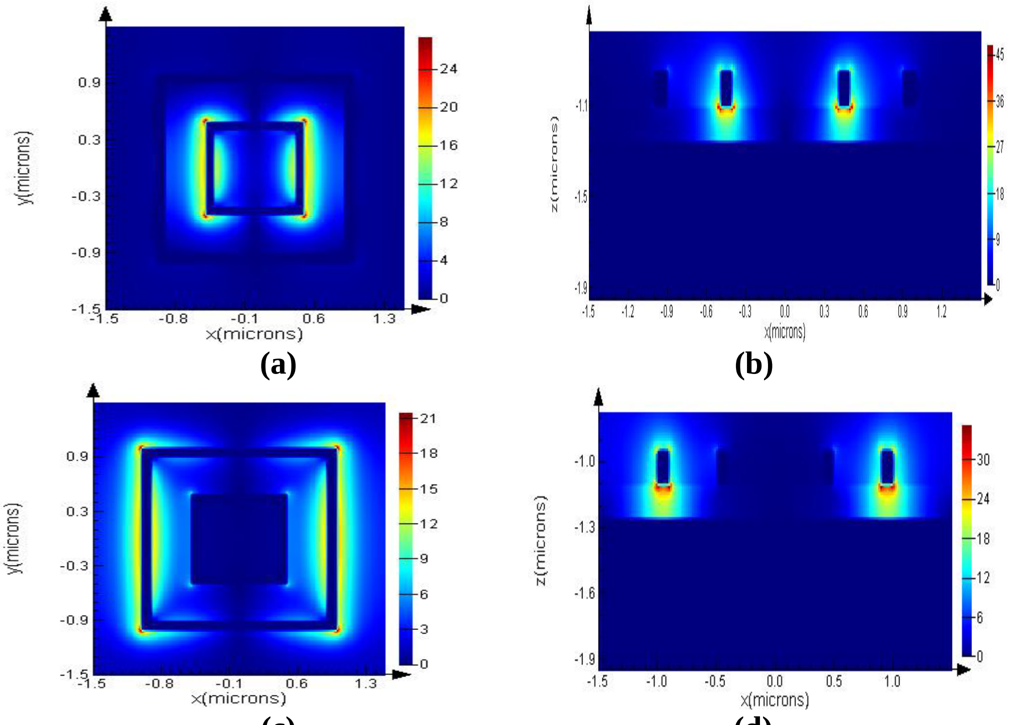
In the eq(3)., Q represents the incident electromagnetic field power per unit area, $S(x,y) = \int_0^T \left|\vec{E} \times \vec{H}\right| dt \Big/ T$ represents the Poynting vector[15,16], T is the surface plasmon resonance period, the absorption and transmission lines of this absorber can be modeled by eq (3).

Definition A is the absorptance of this absorber, this absorber for the surface plasmon resonance absorption loss of the incident electromagnetic wave can be defined by the equation.

$$A = 1 - T - R \tag{4}$$

3. Field energy level distribution and wide-angle absorption analysis

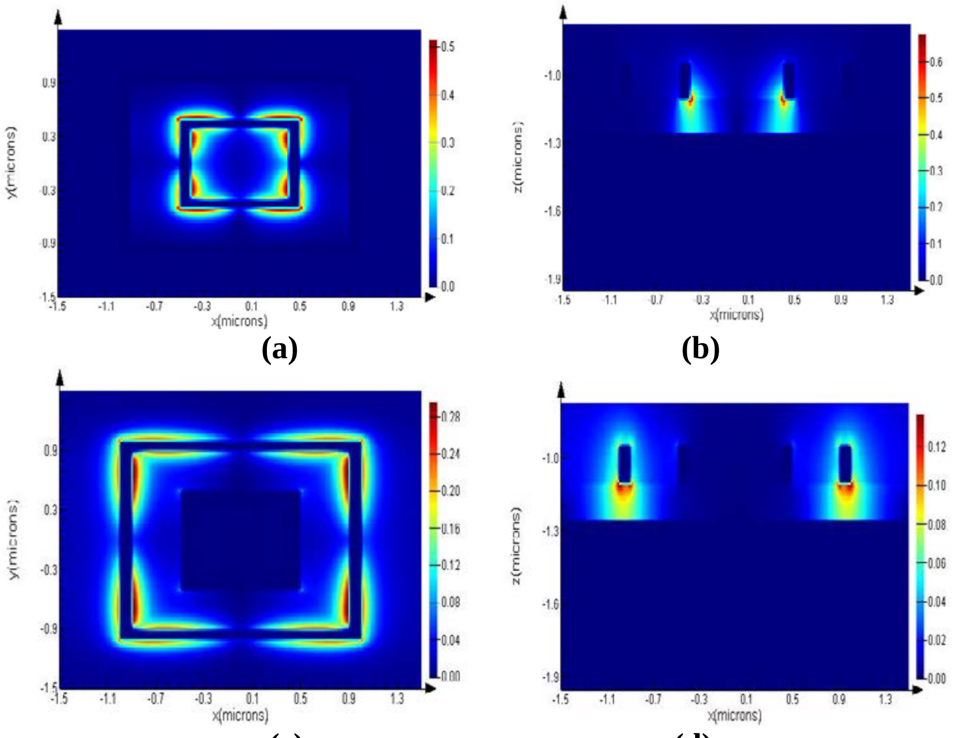
3.1. Field energy level distribution



(a) (b)

(c) (d)

Fig 3 The electric field energy level distribution of the resonance absorption peak of the square ring structure, (a) (b) is the electric field energy level distribution of the resonance absorption peak at 4.75 um, (c) (d) is the electric field energy level distribution at 7.65 um



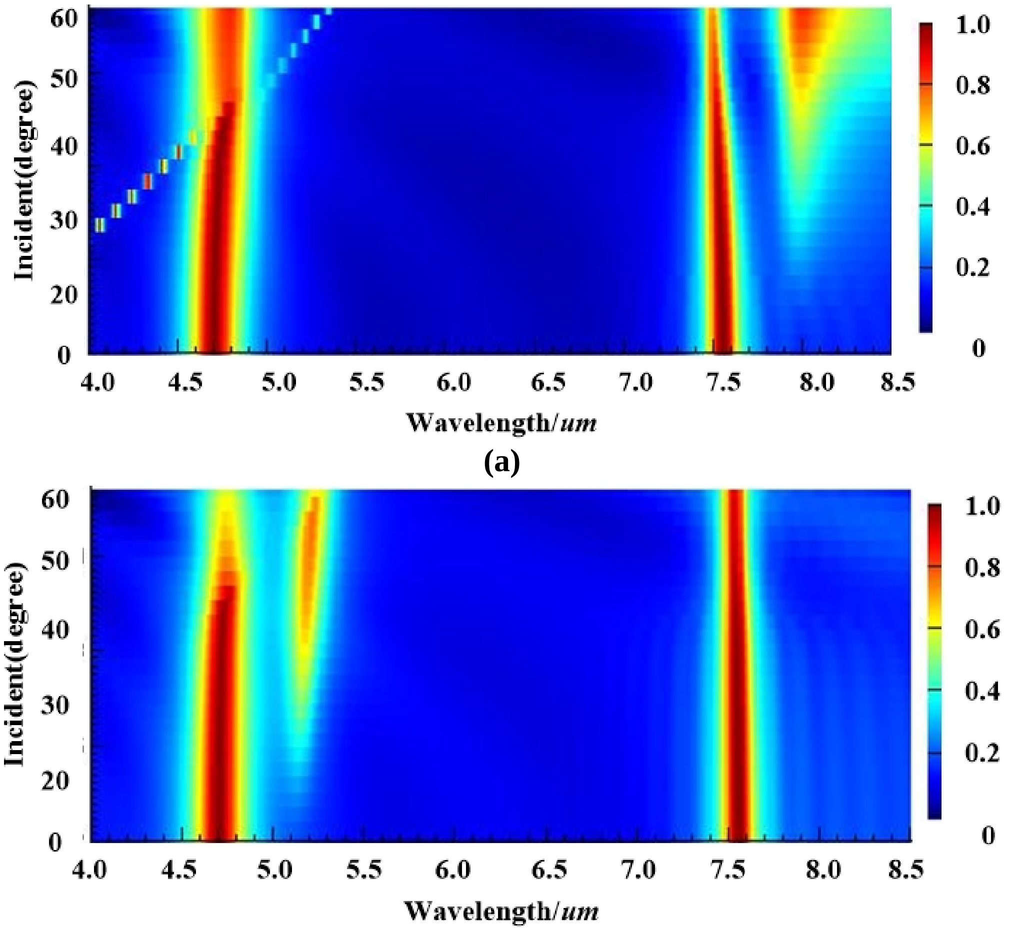
(a) (b)

(c) (d)

Fig 4. The magnetic field energy level distribution of the resonance absorption peak of the square ring structure, (a) (b) is the magnetic field energy level distribution of the resonance absorption peak at 4.75 um, (c) (d) is the magnetic field energy level distribution at 7.65 um

As shown in Fig 3. From the electric field energy level distribution map and the magnetic field energy level distribution map, it can be clearly found that the resonance absorption peak at 4.75um is mainly generated by the supply energy of the internal square ring structure, and it can be clearly seen from the magnetic field energy level distribution map. , the energy is completely concentrated inside the dielectric layer between the square ring structure and the underlying metal barrier layer. At this time, it can be clearly seen that the resonance mode is single, so the half-width of the resonance absorption peak is narrow. Similarly, the resonance absorption at 7.65um The peak electric field energy level distribution map and the magnetic field energy level distribution map show the same resonance absorption mode as the resonance absorption peak at 4.65um, so this structure can achieve two high absorption rates and narrower half-slit widths in the mid-infrared band. resonance absorption peak.

3.2. Wide-angle absorption analysis



(a)

(b)

Fig 5. The absorption of oblique incidence simulation results of the square ring structure, (a) is the oblique incidence chromatogram under TE polarization, (b) is the TM polarization under the intermittent incidence chromatogram

As shown in Fig 5. The metamaterial structure is simulated and analyzed when the incident angles of transverse magnetic waves and transverse electric waves change, and it is found that this structure is extremely insensitive to the angle change of incident light, whether it is transverse electric wave or transverse magnetic wave, when the incident angle is changed. When it is greater than 50 degrees, the absorption efficiency of the resonance absorption peak is still greater than 80%, and the half-width of the resonance absorption peak is also guaranteed to be extremely narrow. Therefore, this structure has extremely strong angle insensitivity characteristics, and at the same time the half-peak width is narrow, indicating that this structure has extremely high sensitivity.

4. Conclusion

In summary, through the analysis of the field energy level distribution of this structure, it can be clearly seen that this metamaterial structure has a relatively single resonance mode, so a higher sensitivity resonance absorption peak can be achieved, and the square ring structure of two different sizes guarantees The frequencies of the two resonance absorption peaks are different, and the narrow half-peak width ensures that this structure has extremely high sensitivity. Through the simulation study of different angles of incident electromagnetic waves, it is proved that this structure has a strong angle insensitivity. characteristic. Since the design shape of this structure is relatively easy to realize and it is relatively easy to prepare in the production process, this structure has strong application prospects in the fields of communication engineering and detectors.

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